THE JET AND THE SUPERNOVA IN GRB 990712[1]

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Draft version February 1, 2008

ABSTRACT

The optical light curve of the afterglow following the gamma-ray burst GRB 990712 is re-examined. Recently published polarization measurements of that source require a collimated outflow geometry that in turn predicts a break in the light curve. We show that the V-band light curve is consistent with such a break and that the post-break light curve evolution is dominated by a supernova contribution.

Subject headings: gamma rays: bursts

1. INTRODUCTION

Optical light curves of gamma-ray burst (GRB) afterglows decay as a power law in time, $F \propto t^\alpha$, with a typical value of the decay index $\alpha \sim -1$. In several cases the light curve has been observed to steepen, about 1–3 days after the gamma-ray event, to $\alpha \sim -2$ or even steeper (e.g. Kulkarni et al. 1999; Castro-Tirado et al. 1999; Harrison et al. 1999; Stanek et al. 1999; Israel et al. 1999; Holland et al. 2001a; Jaunsen et al. 2000; Jensen et al. 2000). Such a light curve is commonly referred to as a broken power law with α_1 denoting the pre-break decay index and α_2 the post-break index.

A generic model that has been successfully applied to afterglow observations is that of a relativistic fireball that sweeps up ambient matter and decelerates. An unbroken light curve can be explained by a spherically symmetric fireball (e.g. Sari, Piran & Narayan 1998), whereas a broken power law in most cases requires a collimated outflow, i.e. a jet (Rhoads 1999; Sari, Piran & Halpern 1999). In the latter case the light curve steepens as the relativistic beaming angle ($\sim 1/\Gamma$, with Γ the decreasing bulk Lorentz factor), increases and becomes equal to or greater than the jet opening angle, θ.

The currently favored model for long-duration GRB progenitors is that of a collapsar (Woosley 1993), or hypernova (Paczyński 1998). Numerical simulations show that as an iron core of a massive star collapses to form a black hole it releases up to $10^{52} - 10^{53}$ ergs of energy, a fraction of which produces a jet and a gamma-ray burst. The remaining energy explodes the star and produces a supernova (MacFadyen & Woosley 1999).

The presence of a supernova is most easily confirmed by studying afterglow light curves. After an initial power law decay of the emission originating in the jet, an underlying supernova is expected to dominate the late time light curve behavior, in most cases appearing a few days to a couple of weeks after the gamma-ray event.

A number of afterglows have been interpreted by such a scenario, e.g. GRB 980425/SN1998bw, an unusual Type Ib/c supernova located relatively nearby, at a redshift of $z = 0.0085$ (Galama et al. 1998). Other cases include GRB 980326 (Bloom et al. 1999), GRB 970228 (Reichart 1999; Galama et al. 2000), GRB 000418 (Dar & De Rújula 2000), and possibly GRB 970514 (Germany et al. 2000; Turatto et al. 2000 and GRB 980703 (Holland et al. 2001b).

One counterexample may be GRB 990712, that apparently did not show a steepening light curve nor a supernova-like component. The optical discovery and early light curve of GRB 990712 was reported by Sahu et al. (2000; hereafter referred to as S00), who found that a decay proportional to t^{-1}, plus a constant host contribution provides a better fit to the data than a t^{-1} power law with a constant host and a supernova of type SN1998bw at the appropriate redshift. Hjorth et al. (2000) discussed the late afterglow properties as well as the host galaxy. Their localization of the gamma-ray burst within the host was based on astrometric data adopted from S00 and turned out to be incorrect. They concluded that no SN component was needed. Fruchter et al. (2000) correctly identified the burst location within the host from its variability.

A set of polarization measurements for GRB 990712, presented by Rol et al. (2000), showed a variable degree of polarization at a constant position angle over a 24 h interval starting about 11 h after the gamma-ray event. Because of the constant position angle, Rol et al. (2000) concluded that none of the currently available models could explain the observations. Björnsson & Lindfors (2000; hereafter BL00) on the other hand, showed that the polarization data is most naturally explained by a collimated outflow that was modestly spreading during the polarization measurements. They estimated the jet opening angle, θ, to be about 6°. A consequence of that interpretation is that a break should appear in the light curve about 1–2 days after the gamma-ray event, for the same reason as the break in the light curves of GRB 990123 (e.g. Kulkarni et al. 1999; Castro-Tirado et al. 1999) and GRB 990510 (e.g. Harrison et al. 1999; Stanek et al. 1999; Israel et al. 1999; Holland et al. 2001a).

Prompted by the BL00 prediction, we have reanalyzed the V and R band light curves of GRB 990712. We show that a break indeed appears to be present in the V-band at the time predicted by BL00. As a consequence, a prominent supernova-like component appears in the post-break light curve that is also clearly observed in the R-band where no sign of a break is detected. The data provides a tantalizing case for the GRB/SN connection. Throughout, we assume a cosmology with $H_0 = 65 \text{ kms}^{-1}\text{Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$

2. THE OPTICAL LIGHT CURVE

The optical light curves of GRB 990712 in different bands all seemed to decay as t^{-1}, with a single power-law decay plus a constant host contribution providing the best fit to the data (S00). In these fits, however, the host magnitude was a free parameter in each band. Adding a supernova component of type SN1998bw at the appropriate redshift did not change the derived decay rate. As noted by S00, a decay rate of $\alpha \gtrsim -1$, continuing indefinitely, would imply an infinite energy release in the burst. Therefore, light curves decaying with $\alpha = -1$ or slower are required to break or bend.

Here, we use the ground based measurements of the host magnitudes, $V = 22.40 \pm 0.08$ and $R = 21.91 \pm 0.04$, as determined by Hjorth et al. (2000), reducing the number of free parameters. We concentrate on the V-band as the host is relatively faint there. In Fig. 2 of S00, the three data points on July 14 may indicate a break in the V-band. We therefore adopted all V-band data from S00 and re-reduced the subset of all publically available ESO V-band data for consistency and independence. We also included the *HST* data taken 47.7 days after the burst (Fruchter et al. 2000), assuming a power law spectrum to convert the STIS magnitude to a V-band magnitude. Our V-band data, measured using aperture photometry, is presented in Table 1. The R-band data is taken unmodified from S00 as the re-reduction of the V-band data turned out to be unnecessary. The I-band data points are too few and far between to allow a reliable fit, in addition to an unknown host magnitude in that band.

Our V-band light curve is shown in Fig. 1, with the host magnitude subtracted. Also plotted is a broken power law fit to the light curve prior to day 7. We find that the initial light curve decay has a power law index of $\alpha_1 = -0.83 \pm 0.03$, while $\alpha_2 = -3.06 \pm 1.28$, with the break occurring at $t_b = 1.61 \pm 0.19$ days ($\chi^2_4 = 0.434$, where $\chi^2_{\text{DOF}} = \chi^2/\text{DOF}$, is the reduced χ^2 of the fit). We note that α_1 is significantly larger than the slope reported by S00. An unbroken power law fit to the entire data set results in $\alpha = -0.82 \pm 0.03$, but the fit is considerably worse ($\chi^2_9 = 1.73$). To estimate the effect of the uncertainty in the host magnitude on the decay rate we subtracted several host magnitudes from the light curve. Varying the magnitude in steps from $V = 22.32$ to 22.55, resulted in an increase in α_1 from -0.85 ± 0.04 to -0.79 ± 0.04.

The post-break decay slope, α_2, is very sensitive to the break time. If we fix the break time at $t_b = 1.5$ days, then $\alpha_2 = 2.42 \pm 0.52$ ($\chi^2_5 = 0.734$). The evidence for the break is not very strong, however, as it hinges mostly on one data point (July 14.787), the reliability of which we are unable to verify (adopted from S00). Leaving that point out, a single power law fit to the entire data set gives

$\alpha = -0.81 \pm 0.03$, ($\chi^2_8 = 0.696$).

A break at $t_b \approx 1.5$ days would be in an agreement with the BL00 interpretation of the polarization data, that the observed early light curve results from a sideways expanding jet. The light curve in that model should steepen by $\Delta\alpha = 1 - \alpha_1/3 = 1.28 \pm 0.01$, quite consistent with the observed steepening of 2.23 ± 1.28.

We show the R-band host subtracted light curve in Fig. 1. It differs from the V-band light curve in two important ways. Firstly, it is decaying somewhat faster than the V-band. A fit to the data from the first 4 days results in $\alpha = -0.94 \pm 0.02$ ($\chi^2_{11} = 1.39$), that is consistent with the S00 result. Again, using host magnitudes in the interval $21.74 - 21.95$, we find increasing decay rates in the range -0.98 ± 0.02 to -0.91 ± 0.02, respectively. Restricting the fit to the first 1.5 days does not affect this result. The difference between the early V-band decay rate and the R-band decay rate is significant and is not expected in fireball models, but we have no plausible explanation for it. Secondly, the arguments given in the previous paragraphs, for why there should be a break in the V-band also apply here. No such break is, however, seen in the R-band data.

If the break at 1.5 days in the V-band is real, the late time light curve is seen to be dominated by a component that is first clearly detected at a burst age of about 7 days. Although no break is observed in the R-band, this late time component can also be clearly seen there as a single power law provides a bad fit to the entire R-band data set ($\alpha = -0.84 \pm 0.01$ with $\chi^2_{16} = 8.98$). This late time component appears brighter at earlier times in R than in the V-band and this may be the reason for why a break is not detectable in R.

It is simplest to interpret this late time component as being due to a supernova that rises to a maximum in V of about 23-24 mag at a burst age of 1 to 3 weeks. We also show in Fig. 1, the late time light curve of SN1998bw at the redshift of GRB 990712, $z = 0.434$ (Hjorth et al. 2000; Vreeswijk et al. 2000). The GRB 990712 light curve has a reasonably good resemblance to the light curve of SN1998bw, being almost equally bright in the R-band and somewhat brighter in the V-band. We emphasize that due to insufficient data coverage in the V-band, we have not attempted to fit a broken power law light curve plus a supernova component to the data. We overplot the SN1998bw light curve simply to illustrate the similarity of the GRB 990712 late light curve to it. In addition, it is unknown if SN998bw is typical of GRB associated supernovae. If GRB associated supernovae turn out to be standard candles, fitting late time afterglow light curves to such a standard would provide an independent measurement of the cosmological constant.

3. DISCUSSION

In re-analyzing the V-band light curve of GRB 990712, we have benefited from the measured host magnitudes, reducing the number of free parameters in our fits. The lack of V-band data from day 1 to day 7, makes it difficult to quantify the significance of a break in the light curve. The strongest evidence for a break may come from the light curve and the polarization data *together*, as the same physical model then accounts for both measurements, implying

that that the early light curve is produced in a collimated outflow.

The R-band light curve, although not showing a break and therefore not a clear signature of a jet, does reveal a late time light curve behavior similar to the SN1998bw light curve. A supernova-like component then becomes a necessary ingredient to explain the late time light curves. The argument can also be reversed, because if we accept the late time behavior in the R-band as being due to a supernova, we should expect similar behavior in the V-band. A break in the V-band light curve is then demanded by the data as otherwise an unbroken power law fits the light curve. In addition, energetics requires breaks in the light curves because the decay rates in both V and R are significantly greater than -1.

In S00's fit including a supernova component, it was assumed that it had properties identical to SN1998bw. This is a very strong assumption and, as noted by S00, is hard to justify by current statistics of GRB/SN associations. We choose not to constrain our fit by SN1998bw, but rather use it to demonstrate the possibility that a supernova may have been present in GRB 990712. If the difference between the light curves of GRB 990712 and SN1998bw is real, it may be due to differences in kinetic energy, compo-

sition, explosion geometry or in the properties of the local environment (e.g. Nakamura et al. 2000; Nomoto et al. 2000; Sollerman et al. 2000).

The case of GRB 990712 provides independent evidence from two different sets of measurements for a collimated outflow in a GRB, i.e. the polarization measurements (interpreted by BL00) and the light curve properties (this Letter). The data also shows a strong signature of a supernova like component, especially in the R-band, that in turn requires a break in the early light curve. It is crucial that as complete time coverage as possible be attempted for future optical afterglows for at least a full month, to be able to discern the properties advocated in this Letter. The first few days are most demanding as a break in the light curve is expected to fall within this burst age. It is also important to follow the late time behavior closely to look for a possible supernova accompanying the burst.

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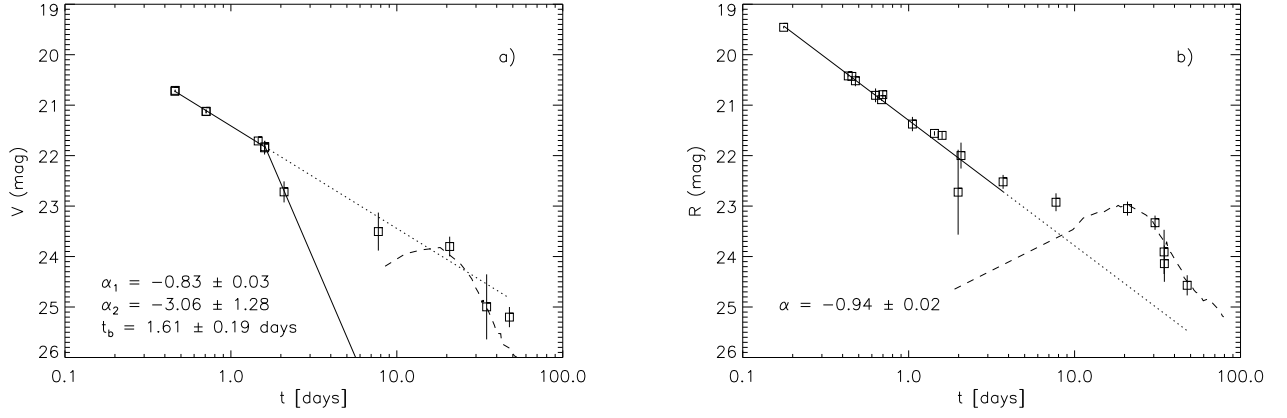Woosley, S. E. 1993, ApJ, 405, 273

Fig. 1.— The left panel shows the V-band light curve of GRB 990712. Note the break after about 1.6 days and the prominent supernova component. The light curve of SN1998bw at $z = 0.434$ is shown dashed. A rather wide gap is in the data at a most crucial interval between 1 and 7 days. The dotted line is an extrapolation of the early light curve. The right panel shows the R-band light curve, again with the SN1998bw light curve superimposed. A solid line shows a fit to the first 4 days. There is no evidence for a break in this case, but the supernova component rises well above the extrapolated power law fit.

TABLE 1
V-Band Photometry of GRB 990712

Day (1999 UT)	Telescope	V magnitude
Jul 13.156	VLT	20.515 ± 0.013
Jul 13.158	VLT	20.500 ± 0.012
Jul 13.405	VLT	20.834 ± 0.026
Jul 13.406	VLT	20.831 ± 0.029
Jul 14.157	VLT	21.248 ± 0.040
Jul 14.292	NTT	21.335 ± 0.083
Jul 14.298	NTT	21.322 ± 0.076
Jul 14.787	SAAO	21.795 ± 0.089[a]
Jul 20.433	NTT	22.065 ± 0.100[a]
Aug 02.511	AAT	22.136 ± 0.042[a]
Aug 16.471	AAT	22.305 ± 0.054[a]
Aug 29.403	HST	25.25 ± 0.2[b]

[a]Taken from Sahu et al. (2000).

[b]OT magnitude